

The pattern speed of the bar in NGC 4596

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ABSTRACT

The pattern speed is a defining parameter of any barred galaxy. A large number of model-dependent techniques have therefore been developed to derive the pattern speed. However, the only model-independent technique for measuring this quantity – the Tremaine–Weinberg method – has hitherto been applied to just one case, the SB0 galaxy NGC 936. In this paper, we apply the technique to a second system, the SBa galaxy NGC 4596. The resulting estimate for the pattern speed is $\Omega_p = 52 \pm 13 \text{ km s}^{-1} \text{ kpc}^{-1}$. This result is corroborated by a spectrum obtained along the major axis of the bar in this system. The corotation radius associated with this pattern speed lies just beyond the end of the bar indicating a fast bar. Combining the bar major-axis spectra with data obtained from a *Hubble Space Telescope* WFPC2 image, we also find strong evidence for a nuclear disc.

Key words: galaxies: fundamental parameters – galaxies: individual: NGC 4596 – galaxies: kinematics and dynamics – galaxies: nuclei.

1 INTRODUCTION

A large fraction of all disc galaxies exhibit central bar-like structures. In a comprehensive review, Sellwood & Wilkinson (1993) estimate this fraction to be 30 per cent. However, near-infrared observations often show bar-like structures where none are visible in the optical images (Mulchaey & Regan 1997). In addition, bars present in edge-on systems are generally not visible, but their presence may be inferred from kinematical observations (Kuijken & Merrifield 1995; Bureau 1998). The occurrence of bars might therefore be significantly higher than the quoted 30 per cent.

Theoretical work on building self-consistent models of barred galaxies has made great strides over the past two decades (e.g. Sellwood 1995). A key parameter in all these models is the angular rate at which the bar pattern rotates – the ‘pattern speed’ of the bar. Unfortunately, comparisons between models and real galaxies are hampered because the pattern speed is difficult to determine observationally. Indirect measurements of the pattern speed based on identifying morphological features like rings with resonance radii (Buta & Combes 1996) or matching a model to the observed gas streamlines (Athanasoula 1992) seem empirically to work quite well and give reliable estimates of quantities such as the densities and velocity fields. However, if we want to relate the theoretical models unequivocally to real galaxies, we clearly need a model-independent way of determining the pattern speed.

Tremaine & Weinberg (1984, hereafter TW) showed that, by invoking the continuity equation, a number of observationally accessible quantities can be related to determine the pattern speed of a bar directly. Application of this technique has so far been

limited to two galaxies, NGC 936 and NGC 4596. Kent (1987) made the first study of the pattern speed, and Merrifield & Kuijken (1995, henceforth MK) refined his analysis using higher quality data. Recently, Bureau et al. (1998) have used this method to measure the pattern speed of a bar detected only in H I in the blue compact dwarf galaxy NGC 2915.

This rather low number of successful applications stems from the difficulty to apply the method in practice. As stars are continually forming and evolving, the continuity equation for both stars and gas is never strictly met. Further, dust extinction can systematically distort both the mean velocity and the mean location of stars along the spectrograph slit. In slightly irregular galaxies, features with different pattern speeds may invalidate the analysis. Finally, the non-axisymmetric signal of a bar is intrinsically weak, so high-quality data must be employed if the characteristic signature is to be detected.

In this paper, we present an application of the TW method to the strongly barred galaxy NGC 4596 using the implementation of this method described in MK. Briefly, this implementation requires the determination of the mean line-of-sight velocities and mean positions of stars along lines parallel to a barred galaxy’s major axis. The mean velocity can be obtained from Doppler analysis of long-slit spectral observations with the slit oriented parallel to the major axis; the corresponding mean position follows from the integrated light admitted through the slit. The pattern speed can then be calculated from the slope of a linear fit between the mean velocities and the mean positions obtained for different slit positions. One asset of this implementation is that the errors are handled in a reliable and quantifiable manner.

The Virgo cluster galaxy NGC 4596 is a very early-type barred galaxy classified as SBa. Its dust mass is only $5.4 \times 10^4 M_\odot$ (Roberts et al. 1991), and its total $B - V$ colour of 0.9 (RC3) implies a star formation rate of less than one $M_\odot$ per yr, a result similar to what is usually found in early type spirals (Kennicutt, Tamblyn & Congdon 1994). The position angle of the bar ($R_{\text{bar}} \sim 4$ kpc) is offset from the major axis by about 45° , the optimal configuration when applying the TW method (see MK).

2 OBSERVATIONS AND ANALYSIS

Long-slit spectra of NGC 4596 were obtained using the blue arm of the ISIS spectrograph on the William Herschel Telescope on 1996 May 22 and 23. The data were obtained using the 1200 line mm^{-1} grating, with spectra centred on the Mg b feature at $\sim 5200 \text{ \AA}$, giving a velocity resolution of $\sim 50 \text{ km s}^{-1}$. Three long-slit spectra, one along the galaxy major axis and two offset parallel to it, were obtained for the purpose of determining the pattern speed. In addition, we obtained a long-slit spectrum with the slit aligned along the major axis of the bar. A schematic view of the slit positions is shown in Fig. 1, and the observations are summarized in Table 1.

The spectra were reduced using IRAF. All frames were bias-subtracted and flat-fielded and corrected for vignetting. The spectra were wavelength calibrated and binned on to a logarithmic scale using the calibration frames taken before or after each exposure. The frames were sky-subtracted, and spectra of foreground stars superposed on the long-slit spectra were removed by linear interpolation. These foreground stars need to be removed because their presence would otherwise affect the mean of the light and radial velocity distributions. Finally, the 20 outermost

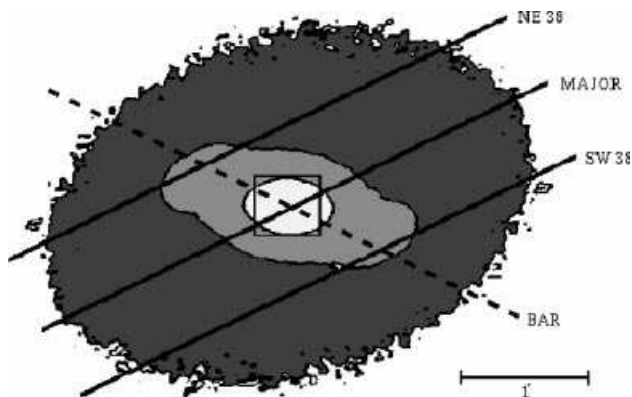


Figure 1. Contours of the bulge, bar and disc in NGC 4596 from Kent (1990) with our observed slit positions overlaid. The slit positions labelled NE38 and SW38 are offset from the major axis by 38 arcsec. The dashed line indicates the position of the bar major axis, where we also obtained spectra. The rectangular box indicates the position of the *HST* image discussed in Section 3.3.

lines of each long-slit spectrum were clipped before averaging the remaining lines to form a single one-dimensional spectrum. The TW method formally requires an infinitely long slit. However, the outermost lines contribute mainly noise instead of signal to the velocity profiles. The pattern speed derived with and without the outermost lines are essentially the same, although the former has an uncertainty that is about 20 per cent larger than the latter.

Velocity profiles for the integrated spectrum were measured using the Unresolved Gaussian Decomposition (UGD) method of Kuijken & Merrifield (1993). This method does not presuppose any specific shape for the velocity profiles, and is therefore particularly well suited to measuring asymmetries in velocity profiles. A K0 giant and a G2V star were used as template stars in this process. Both templates worked equally well. Only for the major-axis spectrum did the K0 star provide a better match to the galaxy spectrum than the G2V star.

The UGD method was applied first using only a single Gaussian component with varying dispersion in order to get an estimate for the velocity dispersion. The mean velocity of the single-component fit obtained along the major axis was taken as the systemic velocity of NGC 4596 and the single-component fits to the two offset spectra were subsequently fixed at this velocity. Then a more complete set of Gaussian components was adopted in order to allow for the departures from Gaussianity in the velocity distribution. The positioning of these components, based on the crude estimate of the dispersion derived from the single Gaussian fit, is described in more detail in MK. A detailed description of the error analysis can also be found there.

The mean position of the stars along each long-slit spectrum was determined by simply collapsing all wavelengths of the long-slit spectrum on to a one-dimensional spatial intensity profile, and then determining the mean of that profile. Errors in this procedure are completely negligible compared with the errors in the mean radial velocity. A summary of the analysis is given in Table 1.

3 RESULTS

3.1 The pattern speed

The resulting velocity and light profiles, together with their respective means, are presented in Fig. 2. The linear fit between the mean velocities and the mean positions along the slit for the three data sets yields a slope of

$$\Omega_p \sin i = 2.4 \pm 0.6 \text{ km s}^{-1} \text{ arcsec}^{-1}. \quad (1)$$

In order to assess the sensitivity of the derived pattern speed to the accuracy with which we have modelled the non-Gaussian nature of the velocity distribution, we repeated the analysis using the single-Gaussian fits to the velocity distribution. The triangular points and dotted line in Fig. 2 show the results of this analysis. There is a slight offset in the mean velocities, but the net impact on the slope of the relation is entirely negligible.

Table 1. Summary of the spectral analysis and results.

Spectrum	Exp. time (s)	PA ($^\circ$)	v_j (km s $^{-1}$)	Vel. disp. (km s $^{-1}$)	$\langle \bar{V}_{\text{los}} \rangle$ (km s $^{-1}$)	$\langle X \rangle$ (arcsec)
ne38	1800	130	1864 (118.0) 2100	71	2010.0 ± 9.2	99.97
major	300	130	1794 (188.8) 2171	118	1973.7 ± 5.4	113.1
sw38	1800	130	1864 (118.0) 2100	71	1946.5 ± 13.5	127.1
bar	1200	73				

The entries for v_j list the minimum, step size and maximum velocities for the means of the UGD components.

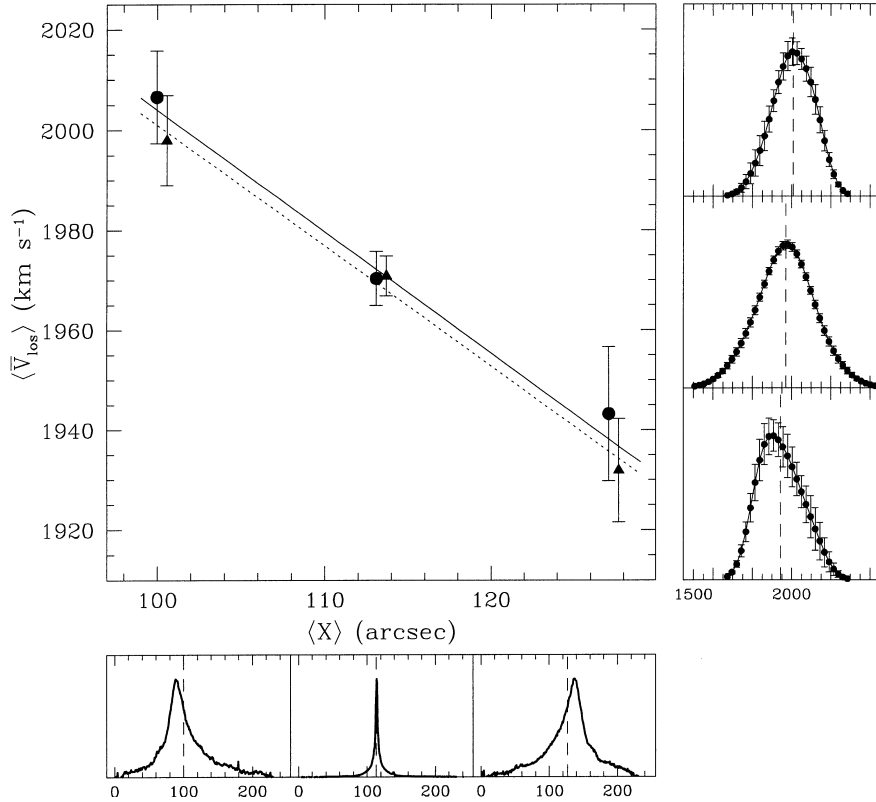


Figure 2. The central panel shows the mean line-of-sight velocities versus luminosity centroid position for the three slits parallel to the major axis (circles). The slope of the linear fit yields $\Omega_p \sin i$ (solid line). The dotted line is a measure of the pattern speed derived assuming Gaussian shapes for the velocity profiles (triangles, which are slightly offset horizontally for clarity). Dashed lines indicate the mean of the light profiles (bottom panels) and of the integrated velocity distributions (right panels) from which the central plot was derived. The velocity profiles plotted here are oversampled, which is responsible for the large error bar on each individual point.

We have also assessed the validity of the error analysis in the estimates of mean velocities (which dominate the total error budget in this analysis). We simulated galaxy data by artificially broadening the template stellar spectra and adding noise. The scatter in the resulting estimated mean velocities was found to be closely comparable to the errors in the estimates. There was a slight tendency for the errors to be overestimated by a few per cent. This effect can probably be attributed to the imposition of a positivity constraint in the derived velocity distributions: this constraint leads to a suppression of the noise in the velocity distribution, which is not accounted for in the error analysis. In any case, this small overestimate in the error analysis makes no significant difference to the derived slope of the line in Fig. 2.

Adopting Kent's (1990) values of a galaxy inclination of $i = 38^\circ$ and a distance to NGC 4596 of 15.7 Mpc, the slope of the line in Fig. 2 corresponds to a pattern speed of $52 \pm 13 \text{ km s}^{-1} \text{ kpc}^{-1}$. This value is marginally higher than, but quite consistent with, the value of $43 \text{ km s}^{-1} \text{ kpc}^{-1}$ that Kent (1990) estimated more indirectly.

3.2 Bar major axis

Corroborative evidence for the derived pattern speed comes from analysis of the long-slit spectrum obtained along the major axis of the bar. The mean velocity as a function of position along this axis was calculated by co-adding adjacent one-dimensional spectra to obtain a signal-to-noise ratio of at least 25. The mean radial velocities of these averaged spectra were then determined directly

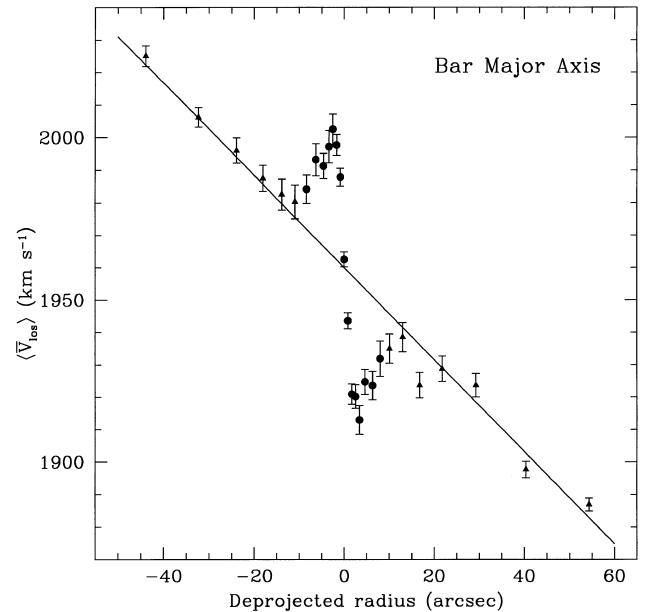


Figure 3. The rotation curve obtained from a spectrum along the bar major axis. Outside the nucleus the bar is rotating like a solid body (triangles), the solid line is a simple linear fit to the triangles. In the inner regions however, a sharp peak in the rotation curve near 3 arcsec is clearly visible (circles).

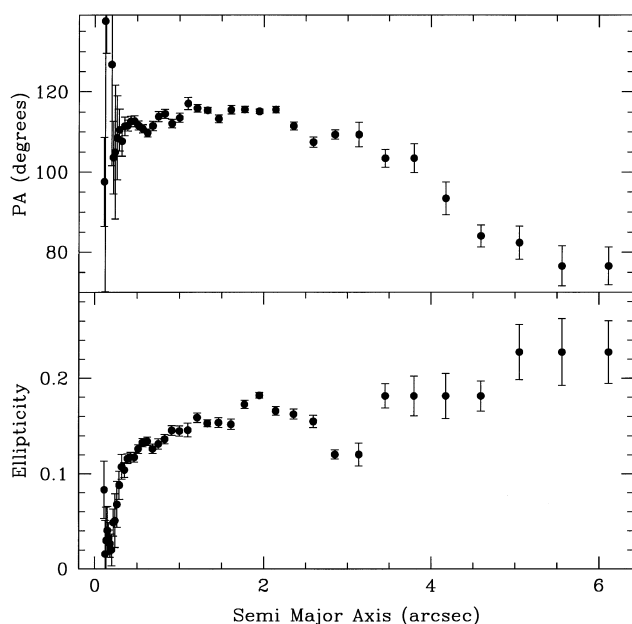


Figure 4. The top panel shows the position angles of ellipses fitted to an *HST* image of the nucleus of NGC 4596. The position angles of the ellipses remain more or less constant within the first 2.5 arcsec and then gradually level off to the position angle of the bulge. In the bottom panel the derived ellipticities as a function of radius are plotted.

in pixel space (van der Marel 1994) assuming Gaussian velocity distributions and using the same giant K0 star used in the derivation of the pattern speed as a template. The resulting rotation curve is presented in Fig. 3. The spatial scale along this position angle has been deprojected to the spatial scale of the major axis.

Outside the central few arcsec, the rotation curve shows solid-body rotation along the bar. A simple linear fit to these data gives a slope of $\Omega_{\text{bar}} \sin i = 1.42 \pm 0.03 \text{ km s}^{-1} \text{ arcsec}^{-1}$. In the plane of the disc, this velocity can be written as the sum of the pattern speed plus the streaming motion in the bar:

$$\Omega_{\text{bar}} R = \Omega_{\text{p}} x + v_R \sin \phi + v_\phi \cos \phi, \quad (2)$$

where $\{v_R, v_\phi\}$ are the polar components of the mean streaming velocity, $x = R \cos \phi$, and $\phi = 63^\circ$ is the difference between the position angle of the major axis (130°) and the position angle of the bar (73°) in the plane of the disc. Along the bar major axis v_R will be almost zero and can therefore be neglected. The x_1 orbits that are believed to make up the bulk of the bar (Contopoulos & Papayannopoulos 1980) rotate in the same direction as the galaxy, so v_ϕ has the same sign as Ω_{p} . Hence, $\Omega_{\text{bar}} > \Omega_{\text{p}} \cos \phi$, which is indeed what we observe $1.4 > 2.4 \cos 63^\circ = 1.1$. Thus the sense of internal streaming in the bar is as expected.

3.3 Nuclear disc

Prompted by the fast-rotating nuclear component apparent in Fig. 3, we extracted a Wide Field Planetary Camera 2 (WFPC2) image of the central regions of NGC 4596 from the *HST* archive. Fitting the isophotes in the innermost few arcsec using the ELLIPSE task in the STSDAS package of IRAF, we found that the isophotes are all aligned in the central ~ 3 arcsec with the galactic disc. At larger radii, the position angles of the ellipses gradually level off to the position angle of the bar (see Fig. 4).

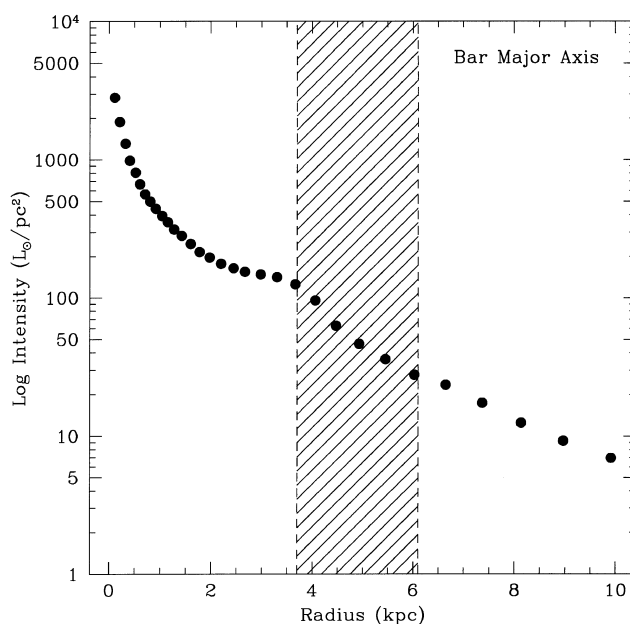


Figure 5. The luminosity profile along the bar major axis derived from the data published by Kent (1990). The profile shows the flat bar plateau commonly found in early-type galaxies. The hatched region denotes the range in which the corotation radius lies.

The dimension of the area of constant position angle closely corresponds to the radius at which the peculiar peak in the rotation curve occurs. Kent (1990) also observed this peak in his long-slit spectra, and found that this feature is strongest along the bar major axis. If we can identify this area with a nuclear disc, its position angle coincides roughly with the major axis of the outer parts of the galaxy. The kinematical axis, however, seems to be aligned with the bar. Coupled with the observation that this projected nuclear disc is rounder than the projected galactic disc ($\epsilon = 0.21$), these results imply that either the potential is not spherical in the centre of this galaxy or that the nuclear disc is not in the plane of the galaxy.

4 DISCUSSION

We have made only the second successful application of the TW method for calculating stellar-bar pattern speeds. In order to interpret the result, it is instructive to calculate what is known as the ‘corotation radius’ of the bar, R_{cr} . This radius is the point in the galaxy at which stars rotate with the same angular frequency as the bar pattern. Combining the derived value of Ω_{p} with Kent’s (1990) model for the circular velocity curve of the NGC 4596, we find that R_{cr} is $4.6_{-0.9}^{+1.5}$ kpc in this galaxy. Fig. 5 shows the luminosity profile along the major axis of the bar, with the range of allowed R_{cr} marked. The point at which the bar ends is apparent as the ‘shoulder’ in the surface-brightness profile at a little over 4 kpc. This yields a ratio of R_{bar} to R_{cr} of $1.15_{-0.23}^{+0.38}$. Thus, the bar ends at close to, but a little inside, the corotation radius. MK found the same result when they applied the TW method to the bar in NGC 936.

In a barred potential, the orbits of stars are aligned parallel to the bar distortion inside the corotation radius, but perpendicular to it outside (Contopoulos & Papayannopoulos 1980). As only stars of which the orbits are aligned along the major axis of the bar contribute to its excess density, any self-consistent bar must end

inside its own corotation radius. Thus, the two directly measured corotation radii are as small as they are physically allowed to be. This limit also means that the bars cannot rotate any faster: larger values of Ω_p would correspond to smaller values of R_{cr} , which are forbidden. Thus, these bars can be described as ‘fast rotators’.

The speed at which these bars rotate is interesting because numerical simulations by Debattista & Sellwood (1998), following work by Weinberg (1985) and Hernquist & Weinberg (1992), have shown that bars forming in dense dark matter halos are rapidly decelerated by dynamical friction. Thus, unless we have caught the bars in NGC 936 and NGC 4596 exceptionally soon after they formed, these galaxies cannot contain centrally concentrated dark matter haloes. This conclusion conflicts with the results of some cosmological cold dark matter simulations of galaxy dark halo formation, which predict that all galaxies should form with a common centrally concentrated dark matter distribution (Navarro, Frenk & White 1996). These conflicting results could be resolved if the inner part of the halo, i.e. the part coinciding with the bar and the disc, somehow acquires a net rotation. Tremaine & Ostriker (1998) have identified a number of possible mechanisms that can spin up the inner halo.

However, it should be borne in mind that high halo densities in the cores of galaxies also serve to inhibit the formation of bars (Ostriker & Peebles 1973). Thus, these two galaxies, which were chosen specifically because they contain strong bars, may constitute a biased subset of central halo densities. If we are to assess whether low central dark matter density is a generic property of galaxies, we need to look at the pattern speeds of a fairer sample of galaxies, including some with weaker bars.

The results obtained on the blue compact dwarf galaxy NGC 2915 by Bureau et al. (1998) are interesting in this respect. However, in late-type galaxies the underlying assumption of continuity, required by the TW method, will be violated owing to vigorous star formation and large amounts of gas present in these galaxies. It also remains to be demonstrated whether the spiral disturbances in such an H I disc can be characterized by a spatially constant real pattern speed, i.e. no winding or growth.

However, applying the TW method to the stellar kinematics of galaxies of a slightly later type than SB0 (NGC 936) and SBa (NGC 4596), not only seems feasible but it will also facilitate a comparison between the TW method and results derived using gas-flow methods. Another interesting problem that the implementation of the TW method described here could tackle is the direct measurement of the pattern speed of a – fairly open –

spiral-arm pattern (although the spiral pattern has to be steady if these measurements are to succeed).

The galaxy presented here, NGC 4596, is a strongly barred galaxy. It will, of course, be more difficult to detect the kinematic signature of the pattern speed in weakly barred or later-type systems. However, the combination of high throughput spectrographs on large telescopes should soon allow us to meet this challenge.

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